DRAFT

A Proposal to Establish

The Virginia Nanomanufacturing Initiative

Developed for
The Virginia Research and Technology Advisory Commission

Prepared by Virginia's Center for Innovative Technology and
The Initiative for Nanotechnology in Virginia

September 2003

PREFACE

This document is a draft nanotechnology research vision for the Commonwealth developed by Virginia's Center for Innovative Technology and the Initiative for Nanotechnology in Virginia at the request of the Virginia Research and Technology Advisory Commission. The document represents the compilation of many ideas that surfaced over the past four months. The discussion and examples that follow describe research highlights and do not include all of the activities relevant to nanomanufacturing across the Commonwealth, nor all of the researchers who may be involved in this potential project.

This draft is not intended to be the final definition of the research vision but a starting point for the definition. The purpose of this draft is to facilitate discussion and subsequent definition of and commitment to the establishment of a nanotechnology research vision for Virginia.

EXECUTIVE SUMMARY

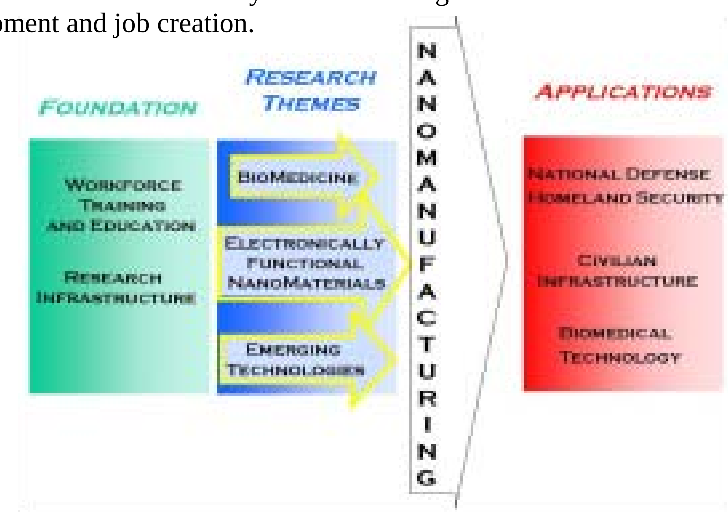
Nanotechnology, the next great scientific/industrial revolution, will bring transformational changes to most industries, and will have a particularly profound impact on health care, homeland security, national defense and the civilian infrastructure—transportation, power generation, communications and information technology. **Despite its great promise, the full potential of nanotechnology cannot be realized until two critical challenges are met: 1) the need to cost effectively manufacture large volumes of nanomaterials and 2) the need to develop a trained nanomanufacturing workforce.** By addressing these challenges, this proposal presents a unique opportunity for Virginia to attain national and world leadership in nanomanufacturing, a capability destined to become the principal economic driver of the 21st century.

Virginia has an existing national recognition in nanotechnology, as the Commonwealth's leading research universities and national laboratories continue to produce groundbreaking work in biomedicine, electronically functional nanomaterials, alternative energy sources, and nanostructured coatings. Additionally, Virginia has existing industrial strengths where nanotechnology will play a critical role. However, Virginia will **only** become the nanomanufacturing leader if targeted investment is made before another region or country capitalizes on this opportunity. With the proper investment, planning, and execution, Virginia will realize substantial job and revenue creation.

The proposed Virginia Nanomanufacturing Initiative (VNI) draws upon the existing strengths of the Commonwealth's research institutions while addressing the need to enhance its research infrastructure (equipment and instrumentation) and take steps to create a trained workforce. An initial $50 million investment is needed to accomplish three critical goals:

- **Fund interdisciplinary, multi-institutional research collaboration projects with industry, focusing on techniques to scale up production of nanomaterials in commercial quantities at competitive prices**
- **Support an enhanced research infrastructure that is broadly applicable and accessible**
- **Establish a statewide workforce development program drawing upon the combined resources of the Commonwealth's K-12 and community college systems, as well as four-year institutions.**

The research funds will be divided among the three core areas: Biomedicine, Electronically Functional Nanomaterials, and Emerging Technologies. Proposed research topics in the core areas include: functionalized carbon nanomaterials, integrated biomolecular devices for pathogen detection, and scaffolds for growth of biological tissues and materials; directed self-assembly of inorganic materials and molecular CMOS IC design and fabrication; and adaptive nanocoatings for civilian and defense application and nanostructured membranes for fuel cell applications. A Research Advisory Committee, comprised of representatives from academia, industry, and government, will review projects based on scientific merit, interdisciplinary nature, multi-institutional collaborations, direct ties with industry, and potential impact on the goals of this program. Similarly, the purchase of new capital research equipment will be evaluated based on the greatest application to key nanomanufacturing research themes, maximum accessibility to users throughout the Commonwealth, and relevance to the goals of economic development and job creation.



With this investment, Virginia will achieve the following goals:

- *Achieve a leadership position in the techniques and materials for nanomanufacturing*. Specific examples include nanoscale materials for medical imaging, biomedical devices, electrodes, circuit elements, photovoltaic films, fuel cell membranes, filters, adhesives and coatings.

- *Create transformational innovations for health care, homeland security, national defense and the national infrastructure.* This will be achieved through dramatic improvements in nanomanufacturing, resulting in greater volumes and lower cost of nanomaterials and devices.

- *Establish the Virginia Nanofabrication Researchers Group* to coordinate, support and build upon the existing research infrastructure across the Commonwealth. This will enable maximum usage of existing and new cutting-edge capital equipment.

- *Develop a Nanomanufacturing Community Network across the state*, a nanobusiness alliance including user groups, periodic conferences, and business development services.

- *Implement coordinated education and training programs in nanotechnology* for traditional university undergraduate and graduate programs as well as K-12, continuing education, and community college training or retraining programs.

- *Provide 50,000 jobs in nanotechnology in the Commonwealth by 2015* through the creation and attraction of nanomanufacturing and related companies. At an average salary of $50,000, this will result in an annual payroll of $2.5 billion for Virginia

Key sections of the full proposal include:

I. Introduction
- Need for enhanced nanomanufacturing capability: Virginia's opportunity
- The Virginia Nanomanufacturing Initiative
- Impact of proposed investment

II. Nanomaterials Research in Virginia: Current Programs and Critical Issues
- Nanomanufacturing in Biomedicine
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III. Nanomaterials Research in Virginia: Proposed Research Directions
- Nanomanufacturing in Biomedicine
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I. INTRODUCTION

Nanotechnology promises to transform most industries and will have a particularly profound impact on health care, homeland security, national defense and the national infrastructure. With federal funding now at $800 million and increasing at a steady pace of 20 per cent per year, nanotechnology is poised to become the largest government science initiative since the space race. And global competition is heating up. According to The Nanotech Report (2003), over $3 billion will be invested worldwide in nanotechnology research and development in 2003, leading to a predicted $1 trillion nanotech industry by 2015. The proposed Virginia Nanomanufacturing Initiative will enable the Commonwealth to attain national and world leadership in nanomanufacturing, a capability destined to become the principal economic driver of the 21st century.

> ***"International leadership in nanotechnology is up for grabs."***
> -The Nanotech Report (2003)

Nanotechnology is **not** science fiction, it is here and now. From tennis rackets with nanotubes (Babolat) to nanostructured running boards for SUV's (General Motors) and stain resistant molecular textile coatings (Nano-Tex) to nanocoatings on Navy ship hulls (Inframat) and germicidal nanocoatings in hearing aids (Germany's Institute of New Materials), nanotechnology is becoming a part of our everyday life.

Despite its great promise, however, the full potential of nanotechnology cannot be realized until two critical challenges are met: 1) the need to cost effectively manufacture large volumes of nanomaterials and 2) the need to develop a trained nanomanufacturing workforce. Until the manufacturing needs are met, the breakthrough discoveries in the laboratory, a direct result of the significant U.S. government research investment, cannot be implemented by the private sector.

Need for enhanced nanomanufacturing capability: Virginia's opportunity

Although the federal government has invested largely in basic research and nanofabrication at the research or prototype stage, there is a recognized need for large volume manufacturing. High volume production is required to develop practical applications of laboratory breakthroughs. For example, a key recommendation of a recent National Research Council report (2003) is that "*The DOD should make investments in research leading to new strategies for the processing, manufacture, inspection, and maintenance of materials and systems.*" Virginia is uniquely positioned to fill this gap with ongoing programs in nanomanufacturing, its highly educated workforce, quality research institutions, and an ideal location (home of the Pentagon, NASA Langley, Jefferson Laboratory, Northrop Grumman Newport News, Naval Surface Warfare Center, Dahlgren, and many primary contractors and subcontractors in the defense industry). The Commonwealth's research universities and institutes of higher learning provide a sound foundation for innovative research and ongoing support for start-up and established businesses. However, Virginia will **only** become the nanomanufacturing leader, resulting in substantial job and revenue creation, if targeted investment is made before another region or country capitalizes upon this opportunity.

> **NanoSensors** for detection of chemical, biological, radiological and explosive agents to protect our military and civilian first responders will develop from advances in *Biomaterials* and *Electronically Functional Nanomaterials*. Increased nanomanufacturing will allow broad dissemination in enclosed public places for ***Homeland Security***.

The Virginia Nanomanufacturing Initiative

The proposed Virginia Nanomanufacturing Initiative (VNI) draws upon the existing strengths of the commonwealth's research institutions while addressing the need to enhance its research infrastructure (equipment and instrumentation) and take steps to create a trained workforce. An initial $50 million investment is needed to accomplish three critical goals:

- **Fund interdisciplinary, multi-institutional research collaboration projects with industry, focusing on techniques to scale up production of nanomaterials in useful quantities at competitive prices**
- **Support an enhanced research infrastructure that is broadly applicable and accessible**
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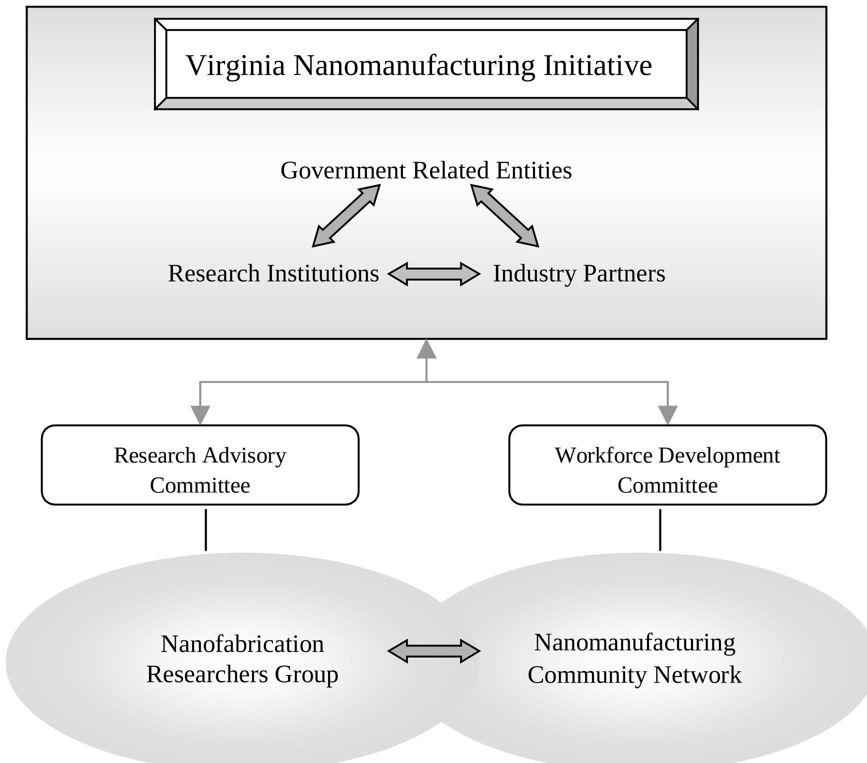
Proposed Virginia Nanomanufacturing Initiative: Structural Features



<u>Core research themes</u>. The research funds will be divided equally among the three core areas: 1) Biomedicine, 2) Electronically Functional Nanomaterials, and 3) Emerging Technologies. These core research themes were chosen because of their natural synergy, potential for significant impact on health care, homeland security, national defense and the national infrastructure, and existing expertise in Virginia. Since fiscal year 2000, researchers at Virginia universities have won awards totaling $10 million in Biomedicine, $30 million in the area of Electronically Functional NanoMaterials, and $10 million in Emerging Technologies.

<u>Research Advisory Committee</u>. A Research Advisory Committee, comprised of representatives from academia, industry, and government will review projects based on scientific merit, interdisciplinary nature, multi- institutional collaborations, direct ties with industry, and potential impact on the goals of this program. Similarly, the purchase of new capital research equipment will be evaluated based on the greatest application to key nanomanufacturing research themes, maximum accessibility to researchers throughout the Commonwealth, and relevance to the goals of economic development and job creation.

Use of funds. Nearly three-fourths of the requested funds will be dedicated to research programs. The research funds will be divided among the three core areas: Biomedicine, Electronically Functional Nanomaterials, and Emerging Technologies. The remaining fourth will be used primarily for research infrastructure (instrumentation and equipment). Funds will also be allocated to support the administration of VNI and the education and workforce development programs.

Impact of selected research themes

Nanosensors for detection of chemical, biological, radiological and explosive agents will help protect our military personnel and civilian first responders. Advances in *Biomaterials* and *Electronically Functional Nanomaterials* will lead to miniaturized, intelligent sensors to provide detection and communication support. Sensing, detection and signal processing at nanometer scales will result in inconspicuous monitoring systems. With increased nanomanufacturing in these areas, adequate supply and lower cost of nanomaterials and components will allow broad coverage of enclosed public places improving *homeland security*.

Nanoporous materials will have a great impact on the personal protection of our military and first responders. These materials are not only superior filters, but due to their extremely high surface area, they can degrade the toxins, dramatically enhancing their protective capabilities. Such materials will have major application in all core research areas: *Biomedical nanomaterials* (sensors and drug delivery), and *Electronically Functional Nanomaterials* (due to inherent dielectric and optical properties), and *Emerging Technologies* (fuel cell performance).

Current Gas Masks utilize WWII -era technology. Use of nanoporous materials will provide new opportunities for increased filtering of nuclear, biological, and chemical toxins.

Semiconductor technologies. An international race is on for new materials that will replace the silicon chip as the basis for computer design. Molecular and quantum devices show great promise, but again, they present major challenges in manufacturing and integration with micro- and macroscale circuitry. These challenges will be addressed within the *Electronically Functional Nanomaterials* research area.

Luna Innovations, with technology licensed from VT, has established a unique (kg/month) nanomanufacturing facility in Blacksburg for Trimetaspheres. Virginia researchers have shown improved image contrast of Trimetasphere-based Magnetic Resonance Imaging (MRI) contrast agents (***Billion dollar/year industry***).

Energy generation. A critical *Emerging Technologies* application will be the use of nanomaterials for optimized performance of hydrogen fuel cells and the development of lightweight batteries for portable GPS systems for troops in service.

Nano-engineered coatings, another area of *Emerging Technologies*, will provide corrosion resistance, flaw detection and self-repair, electromagnetic identification, and "chameleon" camouflage capability for our military's air, sea and ground vehicles.

Instrumentation. As size scales diminish, it becomes increasingly difficult to control, manipulate, and image ("see") the materials to be manufactured. Moreover, important advances are often only achieved after appropriate investigative instruments are available. A recent report issued by the National Nanotechnology Initiative (*Small Wonders, Endless Frontiers*, 2002) recommended enhanced support for the development of the unique tools that enable nanotechnology. Significant equipment to be considered by VNI includes a state of the art Surface Analysis system and a Direct-Write Electron Beam Lithography machine for nanopattern generation without masks.

Impact of proposed investment

With this investment, Virginia will achieve the following goals:

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- *Provide 50,000 jobs in nanotechnology in the Commonwealth by 2015* through the creation and attraction of nanomanufacturing and related companies. At an average salary of $50,000, this will result in an annual payroll of $2.5 billion for Virginia.

II. NANOMATERIALS RESEARCH IN VIRGINIA: Current Programs and Critical Issues

A major challenge in the manufacturing of nanoscale materials is the ability to produce sufficient quantities with the desired structure, chemistry and performance over the necessary range of length scales. Meeting this manufacturing challenge is essential to extending the promise of nanotechnology to a broad range of applications. Within the Commonwealth, programs, capabilities and facilities exist that position Virginia for major breakthroughs in this field, and provide us with a realistic opportunity to attain an international leadership position.

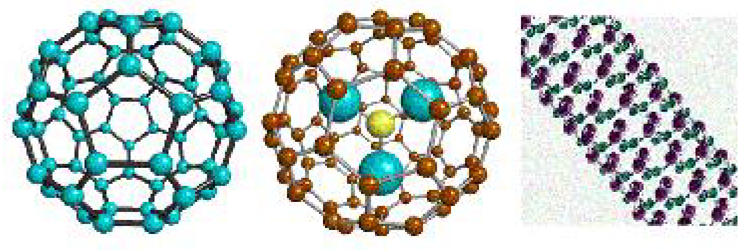
The discussion and examples that follow describe research highlights and do not include all of the activities relevant to Nanomanufacturing across the Commonwealth.

Nanomanufacturing in Biomedicine

<u>Metallofullerenes (trimetaspheres).</u> Nanotechnology promises startling advances in medicine. Unfortunately, much of the what nanotechnology promises has yet to be delivered, as significant scientific and technological barriers remain in our attempts to manufacture such materials in sufficient quantities to make them of practical use. To illustrate, the new carbonaceous materials such as fullerenes, endohedral metallofullerenes, and nanotubes have evolved as perhaps the most important new building blocks in nanotechnology. The development of these new nanomaterials began in 1985 with the discovery of the C_{60} molecule by Smalley, Kroto and coworkers (Rice University). In 1996, Smalley, Kroto, and Curl received the Nobel Prize in chemistry for this fascinating discovery. By 1991, carbon nanotubes had also been identified, followed shortly by the development of endohedral fullerenes (fullerenes encapsulating other atoms). Commercial applications

of these unique materials are now starting to appear. Empty cage fullerenes such as C_{60} are now seeing applications ranging from bowling balls to lubricant additives. Nanotubes are difficult to purify in large quantities, seriously limiting their current applications. However, nanotubes as new field ionizing sources for applications such as electronic displays and new X-ray sources are starting to emerge in significant fashion, especially in Asian markets. The availability of larger quantities of these new carbonaceous nanomaterials is clearly a critical national goal and would serve as essential building blocks for a myriad of new biomedical applications.

In 1999, VT researchers (Dorn and Stevenson) reported in *Nature* (and later licensed to Luna Innovations) an exciting new class of endohedral metallofullerenes. These are very stable high symmetry four atom molecular cluster endohedrals that are formed in a trimetallic nitride template (TNT) process in high yields. The development of this new TNT class of endohedral metallofullerenes (trimetaspheres) has caused great excitement in the chemical and scientific literature. For example, trimetaspheres were recently featured on the cover of both Chemical and Engineering News (June 17, 2002) and Science News (July 13, 2002, see Figure). In 2001-2, Virginia researchers reported the first functionalized trimetaspheres work, an advance cited by Chemical & Engineering News as one of the most important discoveries in fullerene science for 2002.



C_{60} Fullerene | $Sc_3N@C_{80}$ Metallofullerene | Carbon Nanotube

Medical imaging and cancer treatment. **More importantly, Virginia researchers have demonstrated improved image contrast properties of these nanomaterials for applications as Magnetic Resonance Imaging (MRI) contrast agents (*a billion dollar/year industry*), and in therapeutic applications for cancerous tissues.** Luna Innovations in Blacksburg has licensed this technology from Virginia Tech and has established a unique nanomanufacturing facility for trimetaspheres. This facility is capable of producing kg/month quantities of these compounds.

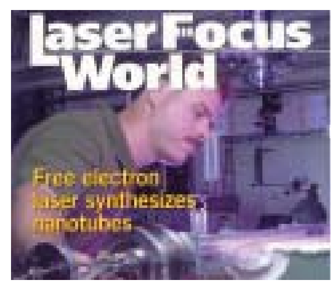
Biopolymers. At VCU, electrospinning of biopolymers has emerged as an effective means for the engineering of cell and tissue scaffolds and controlled drug delivery platforms. However, to date, large-scale production of these bioactive materials with sub-100 nm fibrils remains elusive. The work of Wnek and team (VCU) aims to produce electrospun polymers, such as Type IV collagen, in square meter sheets. **This will enable the preparation of artificial skin and tissue scaffolds that may be used in battlefield tourniquets, wound healing, and other surgical applications.**

Nanobiosensors. The opportunity to directly probe sub-cellular biochemical activity, including the activity of transient biomolecules of various biochemical pathways, is a highly desirable goal in chemical biology. The development of systems of detection, specifically, nanobiosensors and nanobioprobes, that are capable of penetration and location at specific sites within single living cells is made possible through developments in nano-biotechnology. Single walled carbon nanotubes (SWNT), through chemical modification and selective coupling to biological indicator molecules, can enable the development of such nanobiosensors. **The research group of Guiseppi-Elie at VCU has shown that nanobiosensors may be used as alternatives to whole animals in chemical toxicity assessments and may be used in the development of biological warfare agent detection and monitoring systems.** ODU is also actively involved in research focused on the use of carbon nanotube materials for advanced sensors. Large-scale production of carbon nanotubes is absolutely necessary in order to realize these societal benefits. Advances towards this objective include the recent breakthrough by Virginia researchers to apply the Jefferson Lab's Free Electron Laser facility for high-volume production of carbon nanotubes without the need for cumbersome purification steps.

Molecular diagnostics. Luminescent nanoparticles are being developed as highly efficient reporter labels in molecular diagnostics (DNA and antibodies). In the laboratory of El-Shall (VCU), laser techniques are being used to produce highly regular, uniform nanoparticles with consistent optical and electronic properties. Laser techniques, as currently applied, limit production to microgram quantities of nanoparticles. To be successfully applied and developed as a diagnostic reporter label, nanoparticles must be produced in kilogram quantities. **Means must be found to enable the production of large quantities of these highly efficient reporter particles so that they may be used as reagents with high throughput diagnostic instruments and biosensor devices.**

Electronically Functional Nanomaterials

Functional refers to engineered materials possessing optimum properties for a specific application, such as electrical conductivity, thermal insulation, magnetic sensitivity, mechanical strength, corrosion resistance, etc. A major challenge in the manufacturing of nanoscaled functional materials is the ability to produce sufficient quantities that have the desired structure, chemistry and performance over the necessary range of length scales. Not always measured in bulk volume, the production of these nanomaterials may instead refer to the manipulation and control of nanoscale elements over vast arrays. For example, a groundbreaking demonstration of atomic scale manipulation was the use of a scanning tunneling microscope (STM) by IBM researchers to spell out the letters "I-B-M" with individual Xenon atoms in 1989. Significant research programs are currently underway in Virginia, which will provide the foundation for the necessary transition to nanomanufacturing of these materials. **This research area will be critical to the application of many of the programs as nanosystems such as biosensors or fuel cells will be greatly impacted by the ability to integrate with semiconductor technologies.**

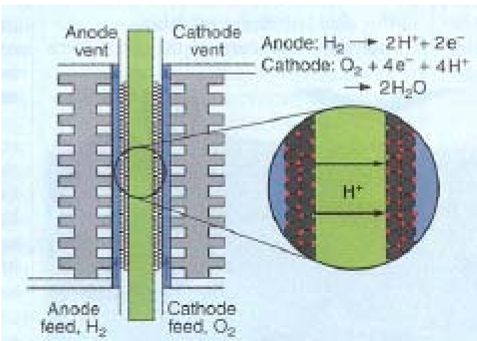


Nano/microelectronics. Virginia has unique expertise in the positioning of large numbers of very small objects whose functionality depends upon controlled interactions between them. In this case the "quantity" is defined by the number of components rather than the volume of engineered material necessary, and the critical challenge is not producing sufficient material, but being able to control the positioning and structure of elements over vast arrays . The key example here is the scaling of microelectronics down to the nanoscale regime. State-of-the-art microelectronic circuits comprise $10^8 – 10^9$ individual components, each engineered with extraordinary precision to integrate with all other components in the circuit. As device sizes in electronics further scale down in size, the numbers of components and required engineering precision continually increase. The key limitation then becomes the ability to define and align structures with sufficient precision (to tens of nanometers or better), and with sufficient throughput. Major Virginia research programs in nanolithography, include nano-contacting techniques (Hull et al, UVA), electron beam writing (Fitzgerald, UVA; Morkoc, VCU), focused ion beam techniques for rapid prototyping (Hull et al, UVA), vacuum and extreme ultraviolet lithography (CWM/JLab), and electron beam projection lithography (Harriott, UVA). Further, because of the limits in scaling of conventional transistor designs, entirely new material sets are being developed. These include patterned arrays of germanium quantum dots for new nanoelectronic architectures such as quantum cellular automata (UVA MRSEC), molecular and biological electronics (Harriott et al, UVA; DiVentra, VT), nanoscale patterned electronic materials (Manos/Holloway CWM), and devices based upon control of electron spin rather than charge (Wadley et al, UVA). Further, Virginia has major existing investments in nanofabrication cleanroom facilities at UVA, VCU and VT, two leading semiconductor microelectronics facilities in the state (Micron and Infineon), a leading nanoelectronics research group at MITRE Corp. (Ellenbogen et al), and highly synergistic activities with national laboratories (Jefferson Laboratories and NASA). It should be noted here that Virginia researchers have been awarded ~$30M in federal grants since FY00 for work on these topics.

Nanomanufacturing of electronically functional materials will result in a continued size reduction, increased processing speed (to Gigahertz (GHz, 10^9 Hz) to Terahertz (THz, 10^{12}Hz) and increased memory capabilities (Terabyte (10^{12} B) capacities).

Nanomanufacturing: Emerging Technologies

Fuel cell enhancement. Our ever-growing demand for energy in the face of dwindling fossil-based fuels presents a national challenge of critical importance. **Nanomaterials show exceptional promise in the areas of energy storage and conversion, e.g., chemical to electrical energy in a fuel cell.** Virginia has a major R&D presence in these areas, and thus significant existing resources can be leveraged.



A Hydrogen-Based Fuel Cell

The adjoining figure shows the principal components of a fuel cell based on the reaction of hydrogen gas (fuel) and oxygen (the oxidant). Nanostructured materials are critical to fuel cell performance. For example, the proton-conducting membrane (in green) contains nano-sized channels through which protons travel between anode and cathode. Each electrode is typically comprised of nano-sized metal particles (typically platinum) on a conductive support at which the essential chemical reactions occur to produce electricity.

Critical issues include: 1) discovery of new materials (membranes and electrodes) that facilitate the development of the proper nanostructures to maximize performance; 2) discovery of new electrode materials that lessen the dependence on precious metals such as platinum; and 3) development of analytical tools to study interfaces between nanostructured electrolyte membranes and electrodes (see magnified area in Fig. 1), which can ultimately dictate performance and long-term reliability. The latter is a particularly thorny issue to address given that chemical and physical events occurring at nano size scales are difficult to access. However, the infrastructure to be developed as part of the current proposal will position Virginia universities and industries to probe this critical yet elusive territory. For example, the pioneering fuel cell research of the McGrath group at Virginia Tech has been supported by major National Science Foundation funding for several years, and is currently poised for further breakthroughs.

Alternative energy technologies. **It is important to note that nano-structured materials will become increasingly important in other alternative energy technologies, including batteries and capacitors.** Critical issues to address are similar to those described for fuel cells, and thus the proposed infrastructure development can be applied to a broad range of problems. In fact, the emerging area of organic materials-based lighting, projected to be a ***multi-billion dollar business within the next decade***, faces similar issues related to nanostructured light emitters and electrode interfaces, and would benefit greatly from our proposed program. Thus, the Solid-State Lighting Initiative being considered for major support by Congress could be significantly leveraged by our proposed focus on nanomaterials manufacturing and its affiliated talent and infrastructure.

Multifunctional surface coatings. Another area of emerging technologies is the method to apply relatively small volumes of nano-engineered materials to large-scale structures through the application of thin coatings or by direct conversion of very thin surface layers by implantation or irradiation. For example to coat a 1000 m^2 of material (i.e. of the order of the surface area of a civil airliner) with a coating 100 nm thick requires only a cubic centimeter of material. **A leading example of such an approach is the DOD-MURI program led by Taylor at UVA, where multifunctional surface coatings are being developed for corrosion resistance, flaw detection and repair, electromagnetic detection, and wavelength adaptability (i.e. "chameleon" capability).** Advanced ALD, sputter, and CVD facilities throughout the state are capable of near monolayer precision and control in deposition of metallic layers. Programs for precise deposition of organic layers for biochemical and other applications exist at several universities. Examples of direct surface conversion can be found in the plasma immersion methods at CWM and in the laser irradiation conversion studies at JLab. Key challenges here include the design and production of such multifunctional coatings, and techniques for reliable and uniform application to large-scale, complex shape structures comprising a wide variety of materials.

Nanoporous materials. Materials have been developed with enormous internal surface area through controllable nanopores. A leading example is the aerogel material produced in Norris' laboratory at UVA. Others include the novel carbon nanoflake material being produced by Holloway and Manos and the nanoclay particles under study by Vold at CWM. Such materials have many existing properties in their own right – such as extraordinary dielectric, optical, chemical, acoustic and thermal properties, but can further be functionalized by controlled incorporation of active elements within the pore array. **Applications include biological sensors and assaying, novel compound magnetic materials, and integrated optically active semiconductor nanostructures.**

Computer modeling and simulation of the behavior of nanomaterials, and in particular their clustering properties, will aid the research and development of nanomanufacturing techniques. Current modeling and simulation programs at GMU may provide insight overlapping the three core research areas discussed above.

III. NANOMATERIALS RESEARCH IN VIRGINIA: Proposed Research Directions

With the proposed investment in nanomanufacturing, it is anticipated that researchers from most or all of the colleges and universities will actively participate in VNI. This includes participation on the individual investigator level as well as via multi-investigator and Center collaboration. The following discussion outlines recommended research directions and identifies a number of leading research projects currently underway.

Nanomanufacturing for Biomedicine

Manufacturing for functionalized carbon nanomaterials. Carbon nanomaterials such as endohedral fullerenes and carbon nanotubes have been at the forefront of numerous discoveries. However, their large-scale application requires platform techniques that allow for the manufacturing of various functionalized forms of the respective carbon nanomaterials that are engineered for particular applications. For carbon nanotubes an additional variable of sorting by size and chirality (both of which eventually affect electronic properties) complicates the development of a platform manufacturing technique for functionalized nanomaterials. Two approaches will be taken to address this issue. Firstly, electric arc methods (which have already been demonstrated by Luna Nanomaterials to be capable of producing kilogram per month quantities of fullerenes) will be integrated with chemical functionalization methods (Dorn and Gibson, VT) to develop a generalized manufacturing technique for these materials. Secondly, Free Electron Laser (FEL) methods, previously demonstrated for production of carbon nanotubes (Laser World Focus, August 2001) with minimal sorting steps, will be scaled up and modified (Holloway and Manos, CWM) to include the functionalization and possible patterning steps. This will enable the manufacture of carbon nanocomposites and other nanomaterials for biomedical and structural applications.

Integrated biomolecular devices for pathogen detection. Fully integrated sample preparation and detection on a biochip platform will enable rapid, point-of-care detection, sub-speciation and potential quantitation of bio-warfare agents (BWA) in the important viral and bacterial groups. Such a screening system will be crucial to the Health Care infrastructure in the event of bio-warfare agent exposure. The vision is to develop such integrated devices so as to allow sample-in: answer-out in *less than an hour* and to use human whole blood, feces, saliva and nasal swabs samples. In order to realize this vision research will be conducted on the development of a silica-based microchip that is simple in design and capable of detecting biological agents in crude biological samples. This will require engineering technologies and chemistries for on-chip sample processing that exploits the unique tunability enabled by sol-gel chemistries and non-contact temperature control of processes that currently exist or are under development within the Diagnostic Biochip Consortium of Virginia (Guiseppi-Elie (VCU), Landers (UVA), Norris (UVA)). These technologies will be integrated with on-chip electrochemical detection for clinical diagnostics, that uses mediating redox layers for amplification and relies upon rapidly evolving MEMS technology.

Manufacturing of scaffolds for growth of biological tissues and materials. Electrospinning has been demonstrated as a highly versatile technique for generating scaffolds for the growth of biological tissues and materials (G. Bowlin, et al at VCU) and is at the forefront of discoveries in the areas of tissue implant materials and wound healing. As part of manufacturing science, the scale-up of the technique and application to larger range of biological tissues and materials will be investigated.

Nanomanufacturing for Electronically Functional Materials

Directed Self-Assembly of Inorganic Materials. The Materials Research Science & Engineering Center (MRSEC) at UVA (PI: R. Hull) has developed numerous directed self assembly methods using Focused Ion Beam (FIB) techniques that utilize surface structure, composition, strain-misfit, and wetting properties to direct the growth of single crystal quantum dots. While past work has developed this technique chiefly for Silicon-Germanium materials, future research directions include extensions towards group III-V semiconductor materials and metal-oxide systems, and application to construct quantum dot nanoelectronic systems using Quantum Cellular Automata (QCA) logic.

Molecular CMOS IC Design and Fabrication. NSF and DARPA funded molecular electronics programs at UVA (Harriott, Bean, and Stan) are focused on studying the integration of these devices with commercial inorganic semiconductor systems and processes, and the architectures and scale-up of system based on molecular devices. Future research directions include the development of vapor phase assembly processes to integrate molecular electronics with existing semiconductor process technology, and the development of functional units such as a bistable molecular gate consisting of either a stacked negative differential resistive (NDR) or memory molecular device as a stepping-stone to molecular adders and microprocessors.

Nanomanufacturing for Emerging Technologies

Adaptive Nanocoatings for civilian and defense applications. Adaptive nanostructured coatings have been at the forefront of many recent discoveries in the protection, modification, power generation, and communication technologies that may be applied for numerous civilian and defense applications. Methods to scale-up the production and reproducibility for such coatings will be conducted as part of this work.

Nanostructured membranes for fuel cell applications. Nanocomposites and nanoparticle membranes have been demonstrated in recent publications by McGrath (Journal of Membrane Science 212 (2003) 263–282) as a necessary stepping to high-efficiency power generation by fuel cells, due to the role of these materials in the reduction of carbon monoxide poisoning and methanol permeation. As part of future work, methods to produce and modify large quantities of such nanocomposites and membranes will be examined.

IV. INSTRUMENTATION FOR NANOMANUFACTURING

Need for imaging. One of the fundamental underlying challenges in nanotechnology research is identifying what you have done. 'Seeing' at the nanoscale involves imaging individual atoms and molecules as well as using instruments that can measure the properties of the atoms of interest, a daunting problem for even well-designed systems and an extremely complex problem when imaging is not the primary goal but only a means of identifying what is happening in a production process. Furthermore, the cost of these types of systems can climb to well over $1 million, which often makes their purchase and maintenance by any individual research group or even a single institution prohibitive.

Current facilities and unique capabilities across the Commonwealth

Virginia's unique resources. To avoid unnecessary duplication, projects funded by VNI will emphasize collaborative use of existing infrastructure. Virginia's unique resources, such as the Jefferson Lab Free Electron Laser, the electro-spin polymer manufacturing system at VCU, the nano-printing, nanopatterning, and epitaxy systems at UVA, and the fullerene synthesis systems at Virginia Tech and Luna Innovations, all have the potential for major advances in all dimensions of nanomanufacturing.

Nanotube production. Researchers at the College of William & Mary are successfully using the Jefferson Lab Free Electron Laser to make carbon nanotubes at very high production rates. This process not only offers the capability to create commercial quantities of nanotubes, but points to a path by which this unique tool may be used to develop methods to separate nanotubes directly during their creation, rather than using expensive and time consuming post-production processes.

Nanolithography. Major experimental facilities exist at UVA and other sites across the commonwealth for nanofabrication of functional materials. This includes instrumentation for nanolithography such as nano-contacting techniques, electron beam writing (VT, VCU, UVA), focused ion beam techniques for rapid prototyping (including a Ga^+ ion Focused Ion Beam (FIB) with controlled deposition, sputtering, or reactive gas etching to provide nanomachining capabilities at a 10 nm resolution), vacuum and extreme ultraviolet lithography (CWM/JLab), and electron beam projection lithography.

Microscopy. Scanning electron microscopes, transmission electron microscopes, atomic force microscopes, and scanning tunneling microscopes are located at multiple sites. These are the primary tools required for all visualization studies of nanometer scale devices and structures. Programs are needed which emphasize novel means of deploying these tools in material development, processing, and characterization.

Spectroscopy. Surface characterization systems such as X-ray Photoelectron Spectroscopy, Auger Electron Spectroscopy, Secondary Ion Mass Spectroscopy, and Ion Scattering Spectroscopy allow researchers to understand the elemental composition and atomic bonding in nanometer-scale materials. Existing systems are located at VT, UVA, and CWM.

Cleanroom facilities allow research teams to construct micrometer and even nanometer scale circuits and devices. These dust and particle free environments are critical for studying nanoelectronic applications as well as creating devices for biosensors and similar devices. Large-scale cleanroom facilities with ultra-filtration are very expensive to construct and to operate; limited versions of such facilities exist at UVA, VCU, VT, and JLab. Smaller scale clean-areas surrounding individual pieces of processing and analytical tools are gaining favor for the research environment. Opportunities exist to promote the foundry-style use of very large state-of-the-art cleanrooms such as those of Virginia's Infineon and Micron, corporations already closely allied with universities in the Microelectronic Consortium.

Instrumentation needed to enhance Virginia's nanomanufacturing research capabilities

We propose a concentrated, overarching effort to build the breadth and depth of scientific capital equipment available for nanoscale characterization necessary to support the activity outlined elsewhere in this proposal. State-of-the-art characterization equipment will be purchased and supported via funding from this collaboration and made available to all nanotechnology researchers operating under this collaboration. A three-step process will be used to identify and determine the equipment purchased and its location:

1. Highest priority will be given to equipment that can be used in direct support of multiple projects across all three application areas.

2. Next will be equipment that can be used in direct support of multiple projects within an application area.

3. Last will be equipment in direct support of one high priority research area, and capable of indirectly supporting other research areas.

The equipment will be located to maximize its use by focusing on a research theme at a given location. Where practical, multiple pieces of equipment will be incorporated into a university- or lab-based user center. This will allow for a critical mass of instrument-based researchers to work together in the same location. If possible, equipment will be networked to permit the possibility of remote operation, to allow researchers to send samples to the equipment site, have them loaded into the instrument queue, and then control the analysis remotely. Technical support for the equipment will be needed to meet the demand created by the diverse research efforts under this collaboration. This will allow more efficient operation of the equipment, support teleoperation, and create a resource for training external personnel and students.

Targeted acquisition of new equipment to compliment the pool of existing Commonwealth resources will create a world-class environment for nanotechnology manufacturing research. Access to a wide range of systems and experienced expert operators to assist in data collection and interpretation will facilitate rapid progress of the greatest number of research projects. Since many of these systems can be used in other areas, they will also foster other research efforts in the Commonwealth. Significant equipment to be considered includes a state of the art Surface Analysis system and a Direct-Write Electron Beam Lithography machine for nanopattern generation without masks.

V. ECONOMIC IMPACT AND WORKFORCE DEVELOPMENT

Economic impact

<u>Projections for job creation</u>. The National Nanotechnology Initiative (NNI) projects a $1 trillion nanotechnology industry requiring 800,000 – 900,000 technical workers in the U.S. by 2015. Worldwide, currently 700 nanotechnology companies are involved in nanotechnology, and $3 billion will be invested worldwide in 2003. Venture capitalists invested $386 million in nanotechnology in 2002, and that number is projected to grow significantly in coming years. Using the NNI projection as a guideline, the Virginia Nanomanufacturing Initiative estimates that 50,000 nanotechnology related jobs can be created in the Commonwealth by 2015. At an average salary of $50,000, this will result in an annual payroll of $2.5 billion for Virginia.

As Virginia attains unique expertise in the fabrication of nanomaterials, there will be a profound impact on the overall economy. Virginia will become the desired location for other high-tech businesses, spin-outs, engineering firms, as well as support service providers such as financial services, law firms, and information technology—employers that will provide additional high paying jobs for Virginians. Overall, this is an optimal strategy to replace traditional manufacturing jobs lost to foreign competitors with access to low wage labor.

Building on existing strengths. Nanotechnology lends itself to many of the industrial strengths that Virginia already possesses. For example, Virginia's diverse economy has many segments where nanotechnology will play a critical role, such as aerospace, microelectronics, chemicals, biotechnology, pharmaceuticals, information technology, automotive manufacturing, telecommunications, and transportation. Also, Virginia is home to the Pentagon, which has resulted in the substantial presence of numerous major federal defense contractors in the Commonwealth. Similarly, the new Department of Homeland Security is a well funded agency that offers Virginia the unique opportunity to become the preferred location for primary and subcontractors focused on this rapidly expanding market. With a total workforce of over 3.9 million, with skilled people who have a reputation for performance, Virginia is well positioned to take advantage of the many new jobs that will be created as nanotechnology becomes more accepted and adopted within these industries.

Nanomanufacturing Community Network. VNI proposes to create a Nanomanufacturing Community Network, enabling strong effective collaborations among the research, education, and commercial components of this initiative. To accelerate technology transfer and assure sufficient numbers of skilled workers, network will sponsor user groups, periodic conferences and business development services.

Supporting business start-ups. Virginia has an existing national recognition in nanotechnology. Recently Small Times magazine honorably mentioned Virginia as a state focused on advancing nanotechnology research and promoting the emergence of companies from the laboratory. In coming years, Virginia will see increasing numbers of spin-offs from universities, federal labs, and existing companies. However, most activity in the near future will be in research and technology development, with large-scale commercialization taking place in 5-10 years.

Additionally, Virginia has excellent support resources in place for spin-out and other start up companies in nanotechnology. The Technology and Business Center at the College of William & Mary, Spinner, Inc. at the University of Virginia, and the Business Technology Center at Virginia Tech all provide business and marketing assistance to early stage companies. The BioAccelerator in Springfield, which already houses a nanotechnology company, the Virginia Biotechnology Development Center in Richmond, North Fork Technology Park in Charlottesville, and the Corporate Research Center in Blacksburg are additional resources that can support young nanotechnology companies. The Center for Innovative Technology's Growth Acceleration Program is one of several vehicles to provide capital and access to capital to Virginia companies with high potential for growth and commercialization. In these early stages of nanotechnology commercialization, VNI will rely on these established resources, laying the foundation for an explosion in new business creation in 5 to10 years.

Workforce development

For Virginia to become the destination for the creation and relocation of nanomanufacturing businesses, a trained workforce must be available. According to the National Coalition for Advanced Manufacturing (NACFAM), nearly 60 percent of the new jobs in the knowledge-based economy of the early 21st century will require skills that are held by just 20 percent of present workforce. VNI will enable prepare Virginian's for the nanotechnology economy through educational and workforce training programs. The experience gained from existing distance learning and training programs (JMU, VT) will serve as a foundation for the development of programs focused on nanomanufacturing.

60% of new jobs will require skills held by just **20%** of current workforce.

Curriculum development and teacher training. In order to train the technical workers needed, VNI proposes a $1 million workforce development program, including classroom and distance education modules for Virginia's K-12, community college, and university systems. A statewide coordinated curriculum centered on nanomanufacturing will be developed across the Commonwealth. K-12 education will initially draw from the considerable resources that have already been developed, in particular the programs that have been funded by the National Nanotechnology Initiative. These resources include classroom demonstrations, lesson plans, simple experiments, and teacher training programs, all of which can be tailored within the framework of Virginia's Standards of Learning. Teacher workshops and summer training programs will be targeted for K-12 and community college faculty. The development and implementation of the education program will be performed in conjunction with proposals submitted for funding to the National Science Foundation, in programs specifically tailored to this purpose.

Job retraining. Retraining of non-traditional students and the existing workforce will take place with industry guidance through VNI's Nanomanufacturing Community Network. Industry-led skill standards will be integrated into education, and training programs and certification systems will be developed. This will ensure the critical skills needed by the nanomanufacturing industry are available, making Virginia the preferred location for creation and relocation of this important sector.

APPENDICES

CONTRIBUTORS TO VNI WHITE PAPER
(listed alphabetically)

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RESEARCH TOPIC SUMMARY

Nanomaterials in Biomedicine

Nanotechnology will have a tremendous impact on innovative diagnostic and treatment options. Nanomanufacturing will increase availability of cutting-edge treatment options for all Americans and decrease Health Care costs.

- Pharmaceuticals
  new drugs and drug delivery systems
- Artificial Skin and Tissue Scaffolds
  wound healing and battlefield tourniquets
- Cancer Detection and Treatment Options
  nanobioprobes to evaluate tumors
  localized drug delivery (i.e. extremely localized radiation treatments)
- Diagnostics
- Medical Imaging
- Biosensors
  homeland security
  defense

Electronically Functional Materials

Nanomanufacturing of electronically functional materials will result in a continued size reduction, increased processing speed (to Gigahertz (GHz, 10^9 Hz) to Terahertz (THz, 10^{12}Hz) and increased memory capabilities (Terabyte (10^{12} B) capacities). Integration with semiconductor technology will allow application of biosensors and fuel cell technologies.

- Transformation of Military and Civilian Electronics and Communications
- Transportation Control Systems and Components
- Organic Materials
  lightweight organic light emitting diodes (OLEDs)
  solar panels
- Molecular Memory

Emerging Technologies

Nanotechnology will result in the development of new energy storage and conversion options to decrease America's dependence on fossil-based supplies. Multifunctional nanocoatings and remote sensors will protect our military vehicles and civilian infrastructure. Purification systems, nanofilters and sensors will be improved and developed with Nanoporous materials.

- Energy
  hydrogen fuel cells
  alternative energy sources,
  lightweight batteries for communications and electronics
- Multifunctional Nanocoatings
  "chameleon" capabilities for military aircraft
  flaw detection and repair
  remote sensors for condition-based maintenance of bridges/infrastructure
- Nanoporous Materials
  catalysis, i.e., carbon monoxide mitigation for public health
  portable water purification systems
  molecular filters
  sensors

VNI MISSION FOR ECONOMIC DEVELOPMENT

Mission Statement

The Virginia NanoManufacturing Initiative (VNI) will seek to enhance the quality of life and raise the standard of living for all Virginians, in collaboration with Virginia stakeholders, through aggressive business recruitment, business development, and expansion assistance of companies that focus on the manufacture of nanomaterials, thereby building the tax base and creating higher income employment opportunities in Virginia.

Objectives

To increase job creation
- 50,000 nanotechnology jobs created in Virginia by 2015

To increase direct investment
- $1 billion of new capital investment in Virginia by 2015

To increase announce projects
- 200 project announcements in Virginia by 2015

To increase the access to financial/venture /investment capital that would service the Virginia's emerging nanotechnology community
- Create a Statewide venture capital/investment fund
- Develop the investment community

To increase the access to human capital necessary to support the industry

To increase the intellectual capital to grow the industry

To increase the availability of facilities and infrastructure that would enable the industry to grow and succeed in Virginia
- Recognized hub for nanomanufacturing activity
- Location(s) for VNI – an actual center location(s)
- Center(s) for research – develop partnerships with Virginia universities
- Center(s) for instrumentation
  - Prepare a list of equipment needs
- Develop a method an equipment funding mechanism

To persuade the Governor to establish the Virginia Nanotechnology Initiative (VNI)
- Involve every Virginia stakeholder in VNI
  - Universities
  - Virginia companies
  - State, Local, and Federal Government
  - Regional technology councils
  - Regional and Local economic developers
- Explore partnerships between private and public organizations

To increase Federal funding for nanotechnology in Virginia
- Build a broad based coalition to increase the efforts of VNI

LIST OF ACRONYMS

ALD	Atomic Layer Deposition
BWA	Biowarfare agents
CIT	Virginia's Center for Innovative Technology
CMOS	Complementary Metal-Oxide Semiconductor
CVD	Chemical Vapor Deposition
CWM	College of William and Mary
DARPA	Defense Advanced Research Projects Agency
DOD	Department of Defense
DOD-MURI	DOD - Multidisciplinary University Research Initiative
FEL	Free Electron Laser
FIB	Focused Ion Beam (Microscope)
GMU	George Mason University
IC	Integrated Circuits
JLab	Thomas Jefferson National Accelerator Facility
JMU	James Madison University
MEMS	MicroElectroMechanical Systems
MRSEC	Materials Research Science and Engineering Center
NDR	Negative Differential Resistive
NSF	National Science Foundation
ODU	Old Dominion University
PI	Principal Investigator
QCA	Quantum Cellular Automata
STM	Scanning Tunneling Microscopy
SUV	Sport Utility Vehicles
SWNT	Single Walled Carbon Nanotubes
TNT	Trimetallic Nitride Template
UVA	University of Virginia
VEDP	Virginia Economic Development Partnership
VT	Virginia Polytechnic Institute and State University
VCU	Virginia Commonwealth University
VNI	Virginia Nanomanufacturing Initiative
VRTAC	Virginia Research and Technology Advisory Commission